



EMERGING POLLUTANTS: OCCURRENCE, FATE, IMPACTS, AND APPROACHES FOR DETECTION

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Abstract : Environmental contaminants are the primary contributors to illnesses and fatalities globally at present. The rising trend of urban development and industrial expansion has led to a surge in different kinds and structures of contaminants, which are challenging to identify and analyse due to their elusive nature and intricate origins of generation. Such contaminants have been referred to as emerging chemicals. Hence, comprehending the analytical techniques and health impacts of emerging environmental chemicals is crucial for establishing a more comprehensive knowledge of transmission pathways, guidelines, and alleviation measures. These pollutants' origin, fate, transport, monitoring, and human health impacts are still developing due to narrow tracking analyses and regulatory frameworks. To bridge this information void, the researchers carried out a comprehensive review of the accessible knowledge. The sources of these pollutants, transmission pathways, detection methods, and human health impacts are thoroughly explained. This knowledge interests ecologists and holds particular relevance for health workers.

Keywords: Contaminants, Health impacts, Transmission pathways, Techniques.

Introduction

Emerging chemicals encompass a diverse array of materials of growing concern due to their potential to pose significant threats to the surroundings or exhibit adverse effects on living species (Pérez-Lemus et al., 2019; Enyoh et al., 2020). However, many of these substances lack adequate tracking procedures, and the regulatory process is unknown. The emerging chemicals encompass both artificially produced and naturally arising hormones, nano plastics, pathogens, antibiotics, agrochemicals, medicinal products, personal care products, and their metamorphosis by-products, and various additional artificial organic substances, primarily originating from factories, communal, or farming origin have transformed human lifestyle and is an essential element of human society (Sima et al., 2014; Zhao et al., 2018). For example, medications, a pivotal achievement in the scientific progress of humanity, have extended life expectancy, healed numerous people from fatal illnesses, and enhanced the overall standard of living. This notable achievement has now resulted in their evolution as swiftly expanding ecological pollutants (Ashraf et al., 2022; Vasilachi et al., 2021). Medical remnants have been detected in nearly all environmental systems across every region. This encompasses aboveground water (rivers, coastal waters, lakes, estuaries, soil, seabed), aquifers, and effluent from sewage treatment. They are now ubiquitously present in the Earth's lithosphere and ecosphere. Arctic and Antarctic zones, the Earth's most natural ecosystems, are currently documented to contain medicinal pollutants. Numerous hormone-altering substances, antibacterial substances, and estrogenic compounds have been detected in high Northern Antarctic areas. Medicinal pollutants and their amounts vary widely. Different breakdown speeds result in outcomes ranging from near-complete breakdown to partial breakdown in the

surroundings and water purification facilities. Specific antibiotics trigger neurological adverse impacts by disordering neurochemical emission or operational change of neuroreceptors, the elevation in glutamic acid contents, cytokine secretion, and the alteration of neurovascular barrier penetration (Fröhlich et al., 2016).

Plastics are flexible substances that can be shaped into structures of different dimensions and types. Polymer materials have found applications in diverse items because of their simplicity of production, strong durability, and adaptable characteristics. Even though polymer upcycling and treatment technologies are developing, inadequate waste plastic management remains a worldwide pattern, contributing to uncontrolled discharge into the surroundings. Because of their hydrophobic nature and robustness, plastics can be conveyed from land to marine environments. Once introduced into the surroundings, plastics undergo degradation and breakdown (Cooper, 2012; Masry et al., 2021; Revel et al., 2018). Diverse environmental influences, including hydraulic pressure, ultraviolet illumination, and other physiological processes, contribute to the disintegration into minute particles called nanoplastics and microplastics (Alimi et al., 2022). Ordinarily, plastic particles within the dimension spanning from 5 mm to 1 μ m are denoted as microplastics, while those ranging in size from 1000 nm to 1 nm are termed nanoplastics. Reducing the size of waste plastic from micro-sized to nano-sized will induce a transformation in physical and chemical characteristics. Moreover, their dimension significantly influences the ecological interaction (including accumulation and movement), aggregation characteristics, and toxicology of plastics. Research has suggested that aquatic species may consume plastic particles from aquatic surroundings due to their minuscule dimensions, elevated specific surface area, and resilient cellular penetration, resulting in the aggregation of plastic particles within living organisms and a range of adverse physiological effects. Additionally, living beings are exposed to plastics via the food chain network (Agathokleous et al., 2021).

Various emerging chemicals have been identified in effluent from sewage treatment, fresh aboveground water, aquifers, rainfall, and potable waters, causing novel and significant problems and escalating global public health and ecological issues. Traditional tracking of water purity usually involves physical and chemical techniques. Regardless of their widespread application and notable achievements, these physical and chemical techniques exhibit notable drawbacks, with one of the most prominent being that the determined contaminant dose does not directly mirror the human response and other species to specific water standards. Detectors have been progressively integrated to tackle this challenge as additional equipment for assessing water purity. These detectors rely on the biological reactions of environmental indicators like microbes, algae, and fish to contaminants, enabling them to determine the physiological impacts. Various investigations have explored the sources, transport, interaction between pollutants and the surroundings, and toxicity of numerous emerging chemicals in marine settings, ground, deposits, polluted water, humans, and other life forms. Advanced analytical techniques have been devised to detect contaminants in the surroundings and human bodies. Moreover, various mitigation techniques have been employed to tackle these emerging contaminants. This review details sources, transport, and monitoring techniques for three kinds of pollutants, i.e., pharmaceuticals, wastewater contaminants, and nanoplastics.

Pharmaceutical sources and their fate

Medications and their byproducts are consistently discharged into the surroundings from specific and diffuse origins. Examples of diffuse origins include unmonitored household discharges, farming discharges into water bodies, and airborne removal origins. Following administration, drugs might experience or not undergo biochemical alterations, either facilitated by intestinal microorganisms or biological catalysts, before being expelled (Rivera-Utrilla et al., 2013). These alterations frequently transpire in two stages. In the first stage, hydrolytic, reductive, and oxidative processes transform the original substance into derivatives with gradually enhanced charge separation and dissolvability in water. In the second stage, conjugative processes alter the initial medicinal substance or its derivatives generated in the first stage. Conjugative processes yield water-loving compounds that are readily eliminated or more easily broken down catalytically. Certain combination processes occur on the initial medicinal substance without preceding the oxidative process. Glucuronidation stands out as the predominant combination process for xenobiotics. Altered and unaltered precursor substances are expelled directly into the surroundings via bladder discharge or alongside solid waste. Clofibric acid does not undergo a biochemical oxidative process (Stage 1) as it can be immediately combined and subsequently eliminated. Unutilised and expired medications make their way into the surroundings by being disposed of in basins, pipes, and commodes or discarded with domestic refuse. Currently, in the southeastern region of England, a study discovered that 66% of the populace includes surplus medicines in domestic refuse, 12% dispose of them by flushing down basins and pipes, while merely 22% send them back to vendors for

appropriate removal. Medications discarded in domestic refuse find their way to disposal locations. Subsequently, they transform into subsurface water releases where dumping regions lack appropriate sealing. Substantial quantities of weakly polar and apolar medicines adhere to particulates and residues in wastewater treatment plants, subsequently extracted with the slurry. Deposits used on farmlands as agrochemicals may discharge pollutants into subsurface water networks(Tijani et al., 2013). Dumpsites and their filtrates encompass various pollutants apart from medicines/drugs. The existence of these substances in subterranean water below or downriver from dumping sites affirms this conveyance. Animal pharmaceuticals are present in livestock excrement containment reservoirs or in areas where these residues are spread onto farming fields(Patel et al., 2019).The accumulation occurs, and these substances go into the subsurface water. Medicines in water ecosystems stem from a person's use through the discharge of processed and unprocessed medications, removal of waste pharmaceuticals, and deploying drug-laden substrates immediately in farming areas or waterbodies with ensuing drainage. Modern household discharges are the primary route of medicinal pollution in the environment. Medical discharges harbouring elevated level blends of numerous drugs are the second most substantial release origin(Li, 2014). Livestock expulsion of medications and their byproducts designates livestock farming as the third most significant release origin(M.-K. Nguyen et al., 2023; Shaheen et al., 2022). Drug production, fish farming, and polluted water application in farming are also noteworthy participants. Drug production represents the main origin of pollution, concentrated particularly at the manufacturing sites. However, production facilities raise particular apprehension due to exceedingly elevated discharge amounts. This issue is more critical in emerging countries that lack appropriate wastewater purification. Broadly, production discharges exhibit medicinal amounts between 10 to 1000-fold greater than those in other polluted water types. This unequivocally illustrates that production facilities stand as the predominant medicinal origins. Drugs and hygiene products are conveyed to harvested plants after using processed polluted water or sewage sludge in farming lands. Anesthesia, antibacterials, antimycotics, anti-swelling, antihelminthic medications, and tranquilisers are employed for animal health. These substances enter the ecosystem through livestock healthcare, improper management of waste pharmaceuticals, or animal fodder. The primary pathway for animal medicine's introduction into the ground ecosystem is its use in raised livestock(Parra-Saldivar et al., 2021). Medicinal fish farming facilitates immediate introduction into water surroundings. Original medicines and their byproducts may infiltrate the ecosystem via animal bladder discharge or solid waste. Antimicrobial application in fish farming is rigorously regulated in certain industrialised nations, and only a limited number of antibacterial agents receive application approval. In fish farming, medications are administered by blending them into marine feed(aus der Beek et al., 2016). Substantial quantities of antibacterial agents are employed to attain beneficial outcomes. This results in the buildup of medicinal substances in the deposits and ground. Farm animal breeding, livestock farming, and aquatic farming are notable sectors in China where vast amounts of medications have been utilised and released into the surroundings. The emission-transport-exposure framework simulates the movement of medicinal substances in watery surroundings. It examines (a) the origin of drugs, (b) the route medications have followed from the origin, and (c) the recipient because drugs have minimal variability; marine conveyance is the primary method of ecological transportation, along with transmission through the food web. Following discharge, medications move through the surroundings via various physio-chemical conveyance methods. Adsorption, release, drainage, and decomposition are crucial conveyance methods for medicinal substances. The configurations, forms, dimensions, dissolvability, water-repellency, ionisation constants, distribution coefficients at various pH levels, adsorption release and soil adhesion collectively influence the conveyance and transfer of medicinal compounds in water environments. Medicinal compounds are engineered to be unreactive but experience physical and chemical alterations. Consequently, comprehending the decomposition of medicinal compounds and processes like biochemical transformations, metabolism routes, and adsorption is necessary to anticipate their ecological fate. The large chemical stability of medicinal compounds implies extended endurance in surroundings. Conversely, drug metabolites arising from oxidative, reductive, and hydrolytic reactions are more prone to additional alterations, leading to diminished ecological steadiness. Medicinal compounds can experience three primary ecological fates through biological and non-biological processes(Gaw et al., 2014). The initial process involves decomposition into CO₂ and H₂O(Ivshina et al., 2018). This occurs with aspirin. Secondly, they might be encapsulated in ecological systems or deposited in wastewater treatment plant residuals while preserving their initial molecular configurations(Kumar et al., 2010). This is frequently noticed with hydrophobic and challenging-to-decompose compounds. Another process is the conversion into more lipophobic substances that exhibit persistence. These lipophobic substances flow through wastewater purification facilities and ultimately reach aquatic environments. Various drugs exhibit diverse physical and chemical characteristics; consequently, considerable interaction variations can be anticipated. Dissolvability, water-repellency, and evaporativity influence the fate of pharmaceutical

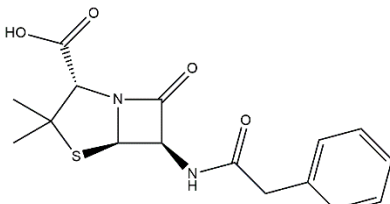
compounds in water ecosystems. Ionisation constants, sorption coefficients, and carbon-specific adsorption coefficients also influence the fate of medical compounds by variations in adsorption, distribution, hydrolytic reaction, photochemical breakdown, and decomposition methods. Stereochemistry is also a crucial variable when evaluating the fate of medicinal compounds. Medicinal alterations rely on numerous ecological settings like acidity level, thermal conditions, and solar radiation, accelerating diverse biodegradation methods.

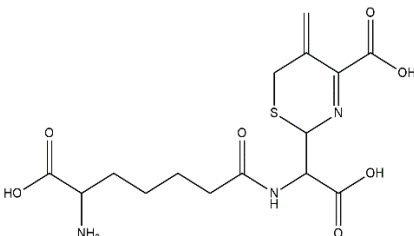
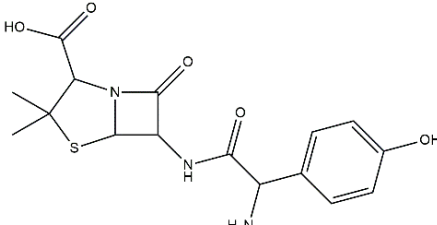
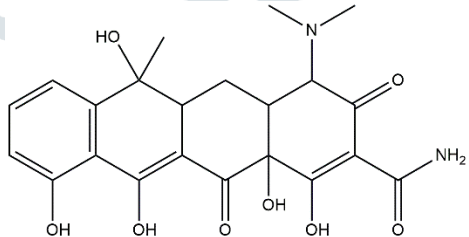
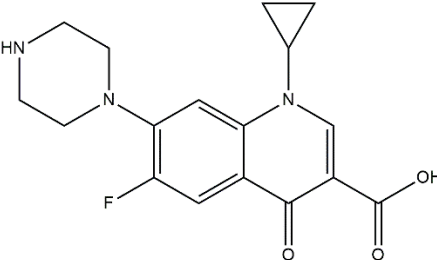
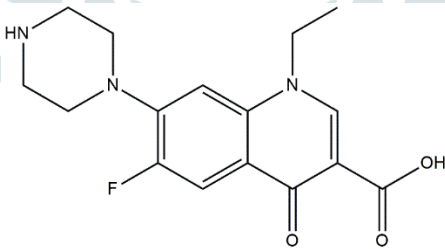
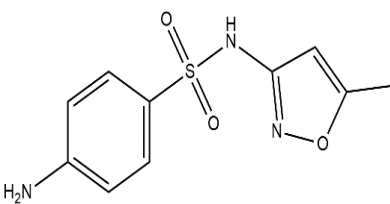
Impact on human health

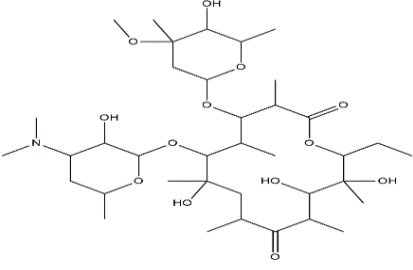
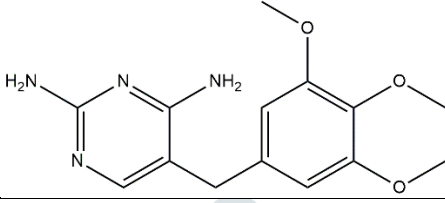
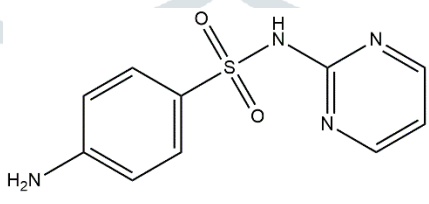
Effect of antibiotics on the brain

In organisms, the neurological impacts of antibiotics were primarily investigated in the medical application scenario. Brain disorder, optic nerve disorder, and epileptic attacks are among the unfavourable neurological impacts linked to their utilisation. It has been demonstrated, specifically, that after medicinal utilisation, specific antibiotics trigger neurological adverse impacts by disordering neurochemical emission or operational change of neuroreceptors, the elevation in glutamic acid contents, cytokine secretion, and the alteration of neurovascular barrier penetration (Leclercq et al., 2017). Embryonic and infancy are pivotal for brain growth (Bercik & Collins, 2014). The disturbance in the systems associated with neural equilibrium in the initial stages of brain growth can result in enduring effects. Foresight research is required to ascertain whether ecological contact with antibiotics directly impacts neural growth or if microbial compounds reaching the neural system disturb genetic function, leading to intellectual dysfunction (P. Wang et al., 2021). In human beings, a study revealed that 70 per cent of European youngsters who were administered antibiotics in childhood exhibited several interpersonal problems, hyperkinetic illness and despair in old age in contrast to youngsters who were not given antibiotics. Animal studies have proved that intake of elevated amounts of antibiotics at pivotal stages for brain growth induces lasting impacts on the neural system. In mice, pre-mating contact with specific antibiotic-induced alterations in behavioural expressions (Fan et al., 2022). Fig. 1 shows the impact of antibiotics on the gut microbiota of rodents and its correlation with behavioural changes. Consistent with this investigation, it was demonstrated that exposing rodents to a lower level of penicillin during the gestational period led to enduring alterations in cortical immune signalling and behavioural changes. It has been recognised that antibiotics like minocycline exert a restrictive effect on brain macrophages—the white blood cells of the cerebrospinal axis. Past research has revealed that the stimulation of brain macrophages is not solely a characteristic of neural inflammation but also holds significance in neural growth. Restriction of brain macrophage stimulation with antibiotics has been demonstrated to trigger brain cell demise and hinder neurogenic processes within the ventricular zone and neuronal elimination in the perinatal and pubescent mice neural systems, respectively. These toxic impacts differ from the brain-shielding functions of antibiotics in grown-up phases. In animals, reports indicate that antibiotic tetracycline can influence the modulation of catalytic enzymes in certain body parts, including the nervous system. It is noteworthy that these enzymes play a significant role in brain macrophages. Hence, alterations in immune cell action may induce significant disruptions if antibiotics are taken during brain growth stages. Neurotoxicity of antibiotics was also observed in marine species. Administering antibiotic norfloxacin to zebrafish impacted the incubation success and the higher death rate and abnormality rate in the prenatal stage (Yang et al., 2020). Furthermore, subjecting to antibiotics triggered intrinsic cell death in the neural system of fish in the prenatal stage. Table 1 shows the side effects of antibiotics on humans.

Table 1 Negative impacts of antibiotics on the human body (Chaturvedi et al., 2021)

Antibiotic	Chemical formula	Structure of antibiotic	Negative impacts
Penicillin G	$C_{16}H_{18}N_2O_4S$		Diarrhoea, type-I hypersensitivity, nausea, neurotoxicity, rash, vomiting, fever, seizures

Cephalosporin	$C_{15}H_{21}N_3O_7S$		Perioperative anaphylaxis, urticaria, positive Coomb's test, serum sickness-type reaction
Amoxicillin	$C_{16}H_{19}N_3O_5S$		Nausea, diarrhoea, vomiting, type I, II hypersensitivity reactions
Tetracycline	$C_{22}H_{24}N_2O_8$		Black hairy tongue, loss of appetite, diarrhoea, nausea, dizziness, sore throat, headache
Ciprofloxacin	$C_{17}H_{18}FN_3O_3$		Vomiting, nausea, pale skin, tiredness, headache, abnormal liver
Norfloxacin	$C_{16}H_{18}FN_3O_3$		Nausea, muscle and joint pain, rectal pain, headache, diarrhoea, dizziness
Sulfamethoxazole	$C_{10}H_{11}N_3O_3S$		Fatigue, insomnia, apathy, nervousness, neuropathy, rash, headache

Erythromycin	$C_{37}H_{67}NO_{13}$		Vomiting, nausea, diarrhoea, cramping, loss of appetite, upper abdominal pain
Trimethoprim	$C_{14}H_{18}N_4O_3$		Nausea, vomiting, headache, diarrhoea, changes in taste, loss of appetite
Sulphadiazine	$C_{10}H_{10}N_4O_2S$		Nausea, vomiting, headache, diarrhoea, loss of appetite

Effect of antidepressants on neural system

Various mental health medications are commonly advised to address psychological conditions like despair, delusion, nervousness, seizure disorder, or emotional imbalances (Carvalho et al., 2016). Hence, antidepressants represent one of the most frequently advised medications in emerging nations. Antidepressants exert their effects directly on neural chemistry by altering neurochemical catabolism. Different antidepressants involve various mechanistic function pathways in the central nervous system, notably controlling the neuro-regenerative impacts (Wang et al., 2018). Different kinds of antidepressants are characterised by their mode of action on neurochemicals. Serotonin booster is majorly advised as an anti-depressant drug and primarily for antenatal depression. The dispersal of antidepressants into lakes, rivers, and marine zones impacts marine species such as fishes, frogs, and snails, inducing changes in social behaviours via cerebral and hormonal impacts. For instance, in eastern gambusia, exposure to the antidepressant fluoxetine induces modifications in antipredator response, aggression levels, and mating behaviours. In the meagre, Duarte and co-authors showcased changes in fish's brain development, oxidative damage, biological detox, and oxidative degradation of lipids in the hepatic organ (Duarte et al., 2020). The findings indicate an endocrine-altering mechanism, suggesting modifications in the reproductive hormone axis. Beyond causing disruptions in marine species, antidepressants accumulate in their neural system, hepatic tissues, and bloodstream (Alvares et al., 2016). Antidepressant medications like fluoxetine are frequently recommended for curing depression in girls during the prenatal or postnatal phase. Given that these medications traverse the maternal-fetal membrane and permeate into mammary fluid, and due to their impact on neurochemical catabolism, it is anticipated that antidepressants may influence the neuro control,

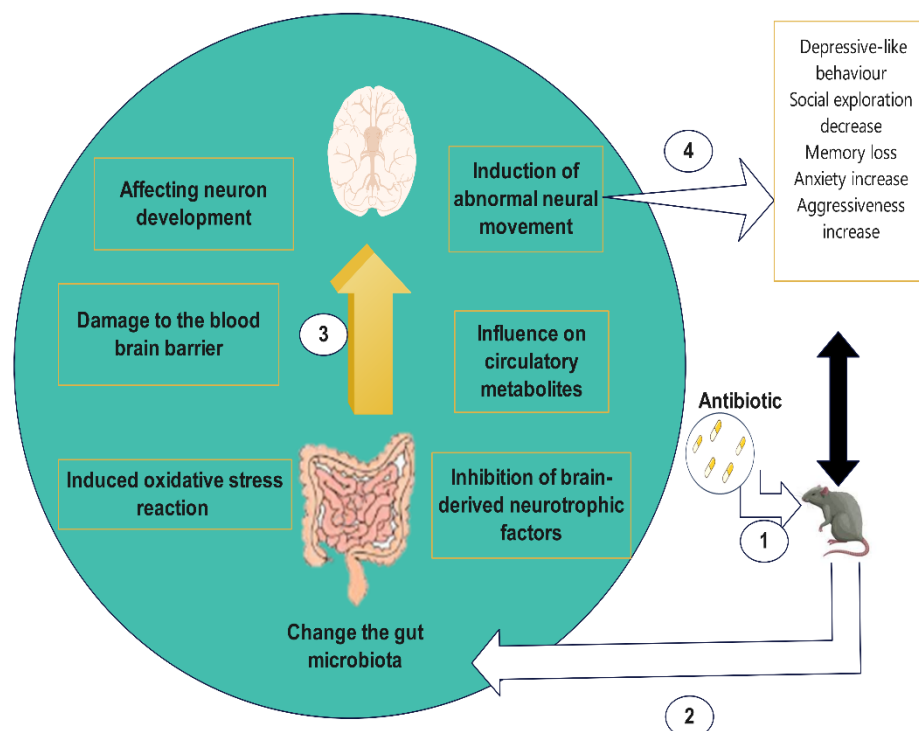


Fig. 1 Interference of antibiotics leads to alterations in the intestinal flora of rats, and the gut-brain connection influences behaviour resembling depression. 1. Rats underwent antibiotic treatment. 2. Antibiotics lead to interference in the gut microbiota in rats. 3. Intestinal flora alterations. 4. Numerous gut and brain-coordinated processes play a role in depression triggered by antibiotics (Hao et al., 2020)

and brain development of the embryo and infants. Consequently, antidepressants can pose enduring repercussions and threats to individual well-being due to their disturbing impacts during the early development stage (Cousins & Goodyer, 2015). Exposing mice to lower levels of antidepressants during the postnatal or prenatal phase has been shown to cause enduring hormonal, social, and neurological changes. The majority of findings were associated with the modulation of the hypothalamic-pituitary-adrenal axis. Exposing mice to a subclass of antidepressant, selective serotonin reuptake inhibitor, i.e., fluoxetine, leads to changes in hormonal and social behaviours in mature women and male offspring during the antenatal stage. Specifically, fluoxetine disturbs hormonal regulation and minimises psychological conditions like despair, delusion, nervousness, seizure disorder, or emotional imbalances in the grown-up stage, which could be attributed to corticosteroid resistance. Exposing male mice during the mature phase to a subclass of antidepressant, selective serotonin reuptake inhibitor, i.e., fluoxetine, leads to a rise in emotional imbalances and disturbs hormonal regulation.

Analytical methods for its detection

Precise recognition and measurement of medicinal substances pose challenges. Complications emerge due to minimal substance levels and intricate matrix influences. Frequently, this necessitates preparatory procedures wherein the substance is separated from complicating matrix substances and condensed to the extent where precise analysis becomes feasible. A standard diagnostic process comprises these crucial stages: specimen gathering and retention, specimen processing (cleansing and intensification), chromatographic division, recognition, and, ultimately, information interpretation. Physical and chemical differences in the substance under analysis imply that a universal approach cannot be employed for all environmental drug monitoring. After formulating a technique, its precision should be verified by assessing removal effectiveness, the method's consistency, and identification thresholds. These approaches can be utilised before and after removal to determine the efficiency of the removal process. The goal of confirming the technique is to affirm the activity metrics established during the procedure formulation. Specimen gathering and conservation sample collection can primarily add to the ambiguity of observations in ecological examination owing to the geographical and chronological fluctuations of contaminants. As a result, obtaining significant analytic outcomes frequently involves handling a substantial quantity of specimens. Effective specimen collection necessitates obtaining a sample size of sufficient magnitude to depict the area of the surroundings being investigated precisely. The more diminished the amount of the substance within the surroundings, the greater the necessary sampling size. Moderately uncontaminated exterior or subsurface water demands a litre of specimen, whereas reduced specimen capacities are essential for denser polluted water. Snatch sampling is the most commonly used

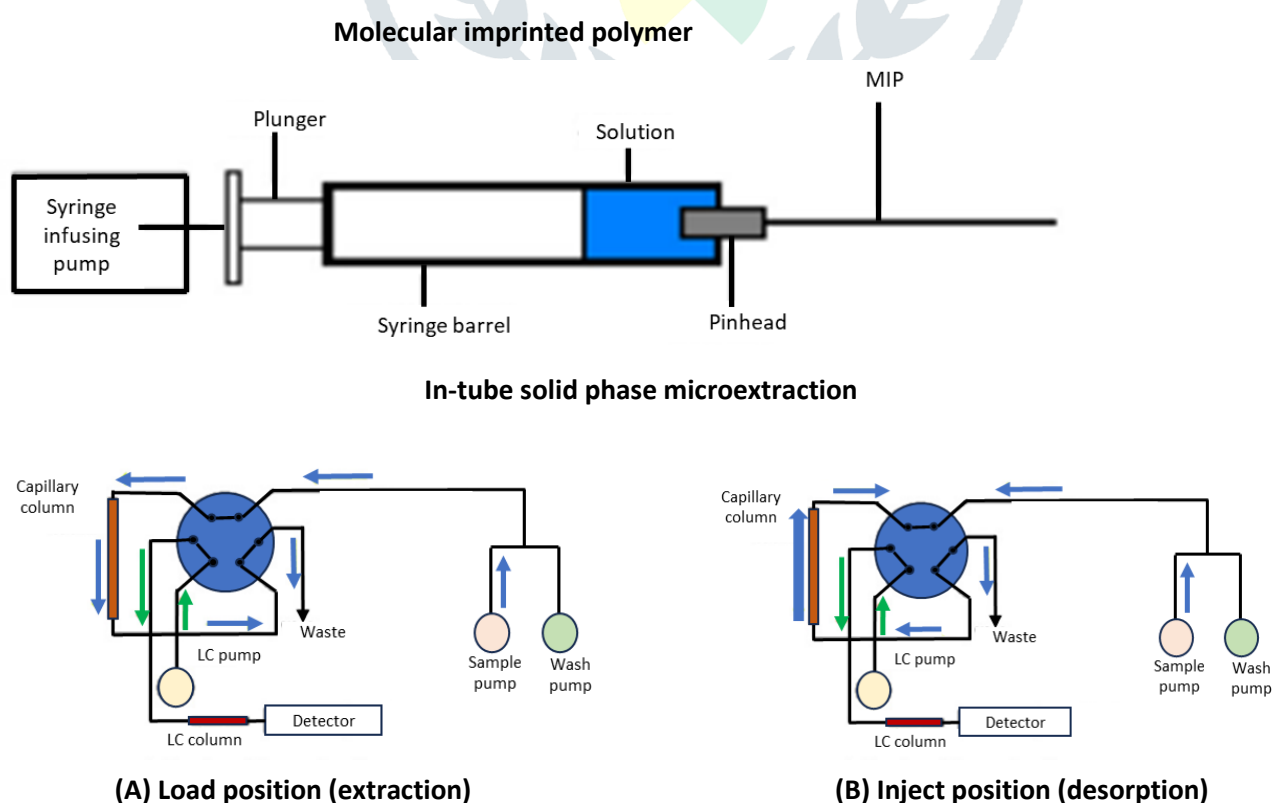
technique for measuring stereoisomeric medications at the highest degree, but this approach can add inaccuracies. Selecting an uncharacteristic site or inappropriate chronology and occurrence of sampling results in fluctuations in contaminant levels that might be inaccurate, as contaminant discharge frequently happens intermittently, not consistently. Gathering grab specimens can be rapid, thus diminishing stereospecific deterioration when appropriate reservoir methods are employed. Mishandling and reservoir inaccuracies may lead to the adulteration or breakdown of specimens. Prompt purification is crucial to eliminate particles that could adversely impact subsequent specimen processing phases. Inadequate storage of specimens may result in the degradation of substances due to ultraviolet irradiation, uncontrolled bacterial processes, and undesired processes.

Solid phase microextraction (SPME)

SPME employs a covered filament to gather and precipitate substances. Subsequently, specimens undergo equilibration. The adhered substances are either desorbed by heat immediately into an analysis tool or released into a solvent solution. Proceeded by analytical examination. Unlike solid phase extraction, this method benefits by allowing reduced specimen size and practical and straightforward specimen handling and removal. Drawbacks involve elevated sensitivity threshold and matrix impacts. The membrane Imprinted Extraction method has additionally been devised to segregate and enhance water-soluble organics from watery mediums. Moreover, adsorptive materials have lately been found to be applicable in examining medicines in the environment. Recognised benefits encompass enhanced selectivity, whereas drawbacks involve escalated expenses and constrained accessibility of particularly molecular imprint phase extraction substances. Fig.2 shows a framework of microextraction techniques for determining hormones in environmental specimens.

Analytical examination method

This method is similar to SPME. Assessment frequently includes a chromatographic segregation phase to separate the objective substance from matrix substances, succeeded by mass spectral identification. Both fluid and vapour chromatography are employed. Fluid chromatography is more prevalent due to numerous hydrophilic drugs' diminished volatility. Their elevated vapour temperature necessitates increased column heat levels, leading to the degradation of many substances during Gas Chromatography (GC). Consequently, an extra modification phase is frequently necessary before the GC examination. The rise in specimen processing duration and expenses constrain the application of this method; nonetheless, it has been utilised for the scrutiny of female hormones and drugs. A variety of sensors can be applied after chromatographic division. Atmospheric Pressure Chemical Ionization and



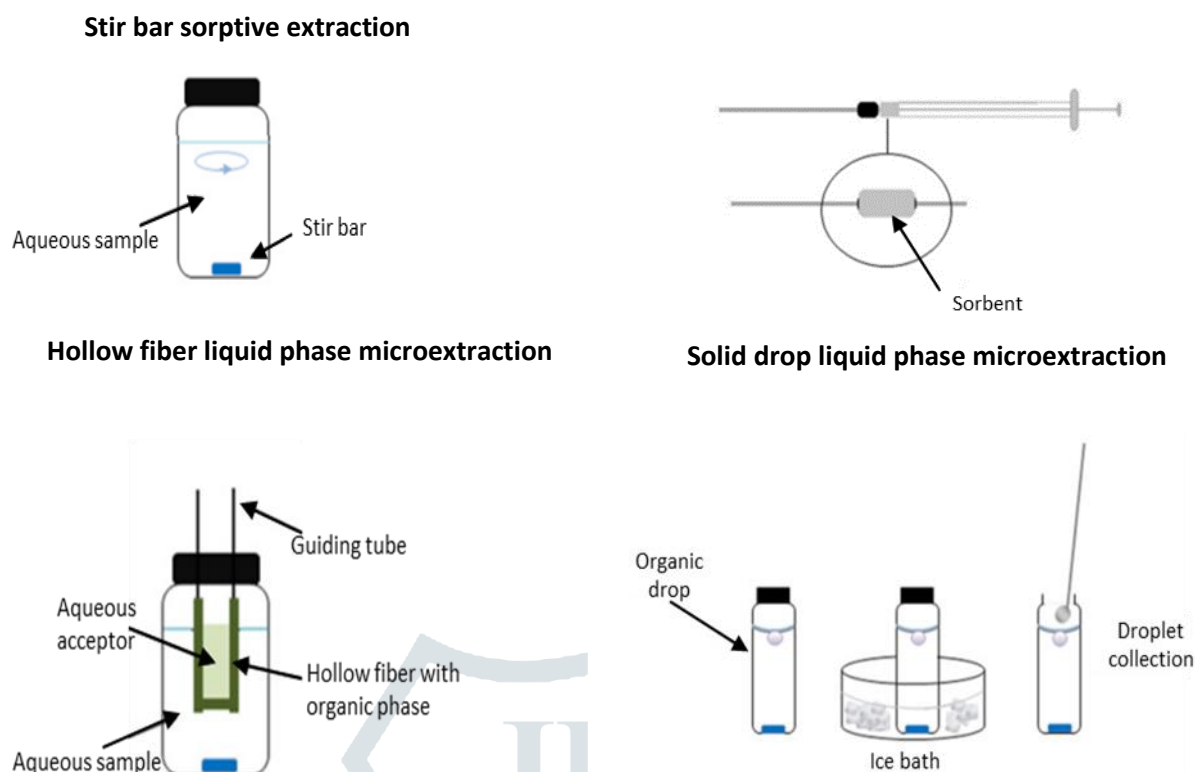


Fig. 2 Microextraction methods employed in the analysis of hormones in environmental samples(Aufartová et al., 2011)

Electrospray Ionization are prevalent methodologies susceptible to the influence of matrix substances. In numerous drug examinations, the peak sharpness of specimens may be considerably diminished owing to matrix effects, leading to a notably lower sensitivity threshold. Complexing substances may be employed in specimen processing to eliminate interfering matrix substances and yield enhanced outcomes. Fluid chromatography sensors for ecological drugs encompass mass analysis, Mass Spectrometry (MS) using time-of-flight detection, and luminescence. Over the last thirty years, Raman spectroscopy has also been extensively utilised to examine biotic and ecological substances, encompassing the sensing of drugs. The possible use of Raman spectroscopy in medicinal examination extends across medicine discovery, manufacturing, quality assurance, and durability assessments. A further application is observed when examining pharmaceutical byproducts during drug movement investigations. The continuous injection method has also played a substantial role in the progress of mechanisation within medicinal study. The fundamental principle of continuous injection involves the injection of a fluid specimen into a constant, unbroken fluid conveyor flow without segmentation. Analysing data involves utilising reference plots generated from standards enriched with the desired compound across a spectrum of amounts pertinent to the methodology, aiding in identifying and quantifying the substances. Matrix impacts represent a paramount consideration when measuring contaminants; hence, reference standards should encompass a comprehensive spectrum of matrix substances for optimal outcomes to minimise potential inaccuracies arising from matrix impacts. In the process advancement, detection and quantification limits are established, yielding the most precise outcomes when working with specimen sizes close to detection and quantification limits. Detection and quantification limits represent amounts yielding signals surpassing the noise level by factors of 3 and 10, respectively. Employing reference standards can enhance evaluation precision. Optimal outcomes are achieved when the reference standard is absent from the surroundings and possesses physical and chemical characteristics akin to the substance under investigation. These reference standards are occasionally utilised and may be introduced before specimen processing for retrieval in the instrumental process, or they can be included in the ultimate residues before the analytical technique.

Quality assurance methodology

This method's calibration should use mixtures with pertinent matrix substance levels to replicate the matrix influence. Removal efficacy in the technique can be ascertained through retrieval investigations. Typically, allowed figures span from 80 to 120 percent. Variability in the methodology is established through the recurrence of removals—usually 3 to 5 iterations. The consistency and accuracy of the instrument are assessed by injecting varied amounts of the substance numerous times. The idea of eco-friendly chemical analysis for monitoring the quality of biogenic contaminants, i.e., drugs, is becoming increasingly popular. The primary

objective of eco-friendly chemical analysis is to attain a more environmentally conscious and enduring investigation, substitute harmful chemicals, and adapt or substitute scientific methodologies. This allows for a significant reduction in the quantities of chemicals utilised and litter produced.

Nanoplastics origin and its behaviour in the environment

The origin of nanoplastics particles (NPPS) in the surroundings are classified as either principal or derivative, contingent on whether they measure less than 1000 nanometers before introduction into the surroundings or attain this dimension through the deterioration and segmentation of more substantial fragments of plastic debris or microplastics, respectively. The fundamental origin of nanoplastics might involve nano-size pieces from laundering garments, minuscule particles discharged from polymer tea sachets, and petite pieces from manufacturing powders(Fig.3). The auxiliary is probably attributed to nanoplastics formation arising from plastic refuse and microplastics through diverse methods in the surroundings. As human-created goods, polymers primarily stem from land-based systems. Nonetheless, because of the gathering of polymer particles in wastewater and discharges, they might eventually amass in water environments. It is approximated that more than 80% of oceanic polymers result from terrestrial origins, like seaside dumpsite management. Waterways transport nanoplastics, nutrient-rich organic matter and decayed plant material are applied, and unprocessed wastewater is inappropriately discarded. Moreover, aquatic origins involve the release of refuse from watercraft and meshes. In this context, comprehending the land-based source of nanoplastics is essential. A primary contributor to plastics is household actions. Minuscule strands of nylon, polyester, and acrylic are transported to sewage management facilities when washing garments. Breaking down microspheres employed in cleansers and exfoliants liberate substantial quantities of plastics. Even synthetic tea pouches might emit billions of nanoplastics. Besides household sources, manufacturing origins encompass the immediate production of nanoplastics and raw materials for polymer items. Moreover, farming practices play a role in the emission of minuscule plastic particles. Using wastewater residue as plant nourishment signifies a noteworthy origin, whereas plastic-covering and plastic-covered emit plant nutrients, and insecticides introduce alternative plausible sources of nanoplastics(Bui et al., 2020). People's existence and actions are indistinguishable from aqueous media; the marine surroundings might be the most extensive repository of nano-sized plastics. As liquid moves, plastic particles can be transported to any location where the liquid travels. The conveyance of nanoplastics in the water setting has been extensively regarded. This method is not solely linked to the traits of the nanoplastics themselves but also relies on the physio-chemical features of the marine surroundings, along with fluid dynamics, adhesion, and absorption by marine animals, which will immediately influence the deposition, re-floating, and travel length of plastic fragments, and finally influence their ecological behaviour. Nanoplastics from terrestrial origins are released directly into streams and ponds, and the outflow is from sewage management facilities or runoff water(Huang et al., 2021).In general, miniature and lightweight plastic fragments are upheld on the liquid surface, while bulky plastic fragments settle at the water's bed. Nevertheless, an abundance of organic matter/minerals and microbes in the indigenous surroundings have the propensity to conglomerate with nanoplastics or amass collectively plastic fragments on their own. Alternating the initial mass of polymers subsequently impacts the sedimentation and duration of stay of polymer fragments. Sure, researchers have observed the features of watercourses.

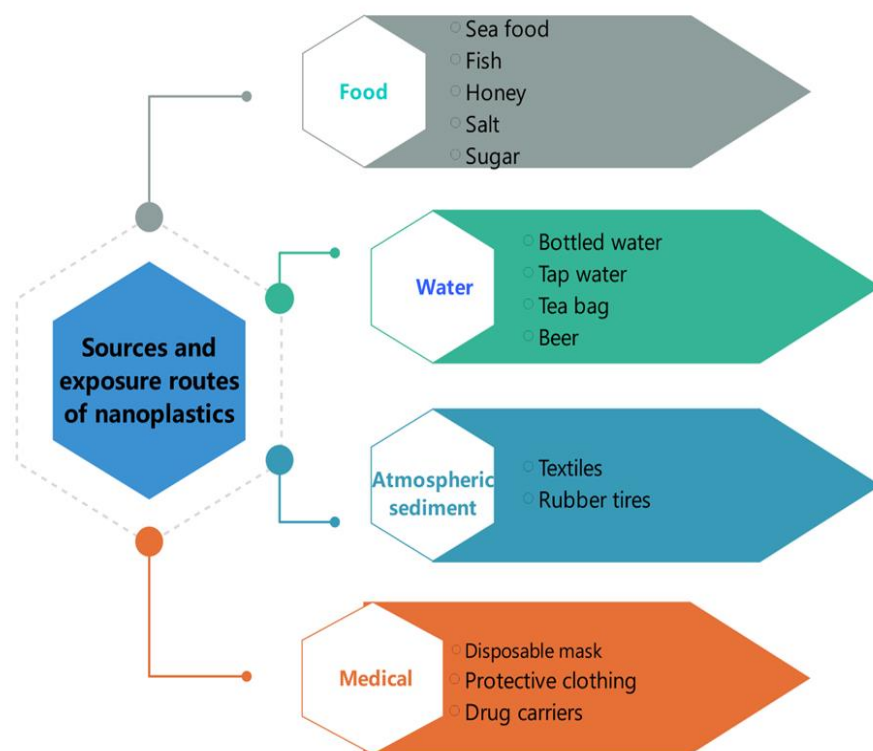


Fig. 3 The sources and exposure routes of nanoplastics(Cheng et al., 2023)

may impact the movement of nanoplastics in the aquatic ecosystem. However, in contrast to aquatic environments, research on pure ecosystems is limited, and most of these studies have overlooked the inherent connection between river hydrology and the conveyance of nanoplastics. The settled plastic particles may find momentarily or perpetually storage in the sediment, whereas the floating plastic will persist in its drift toward the sea. When the river extends into the estuarial zone, on the other side, the flow speed abruptly declines due to the rise in the estuary area. Conversely, the persistent tide flow will restrict the stream water. The ocean water breaks down NaCl molecules, resulting in the production of ions. The three factors above will accumulate substantial sediment, creating a delta. Simultaneously, certain nanoplastics are trapped in the settle in this location. The estuary harbours an elevated level of plastic particles in the distinctive transitional zone between the river and the estuary. However, the number of plastic particles in riverbed deposits surpasses that in the estuaries by a considerable margin. The attributes of plastics in waterways exhibit a consistent pattern, predominantly centered on the configuration of slender sheets and particles. This implies that waterways might face more severe contamination from nanoplastics than oceans. Indeed, plastic refuse from human actions (like harbours, aquatic harvesting, and travel) is also actively released into shoreline waters. Nevertheless, the coastal deposits are inherently variable, contingent on the topography of the border. The sharp, geologically dynamic margins exhibit a slender submerged plateau and a sharp seabed decline, resulting in limited coastal storage capacity. Consequently, this reduces the retention period of deposits and nanoplastics.

Toxic effects

Respiration, skin contact, and swallowing represent potential routes of contact to nanoplastics, as shown in Fig. 4. Inhaling mists containing microplastics and the infiltration of plastic particles into the blood vessels facilitate the dispersion of these micropollutants across the entire body. The plausible interaction of nanoplastic particles with dermal tissue occurs via contact with a polluted atmosphere or water or the application of hygiene products(Lehner et al., 2019). There is uncertainty regarding whether plastic particles can permeate the epidermis. The epidermal layer functions as a hindrance to the skin. Additionally, its water-repellent nature makes it challenging for nanoplastic to infiltrate the skin when exposed to an aqueous medium, but the hygiene components could support the infiltration of nanoplastics. Despite the dissimilarity in surface properties among microplastics and various other nano-sized particles (for instance, quantum nanoparticles), the ingress of nanoplastics relies significantly on the particle dimensions. Broadly, the permeation of the skin could play a role in the absorption of nanoplastics, but additional concrete proof is required. Consuming polluted eatables likely represents the primary route of nanoplastics in the human body. The digestive system, boasting a substantial area of about 32m², stands as the principal location for the assimilation of microplastics.

Nanoplastics might traverse microvilli and access the bloodstream, and the establishment of a polymeric protein complex (commonly referred to as a protein corona) is affirmed by in vitro research. This occurrence is pivotal to the harmfulness of nanoplastics in humans, as the engagements between organs and tissues transpire with protein-covered particles instead of uncoated nanoplastics. Findings from a laboratory-based examination of living organism hematocytes suggest that polymeric protein complex may induce elevated cell damaging and genetic toxic impacts when contrasted with uncoated nanoplastics. This is likely due to the development of bio-coating on the outer layer of nanoplastics, aiding their evasion from the immune network and leading to an extended presence in the vascular system. The attachment process of the bio-coating to nanoplastics is not thoroughly comprehended. Still, it is hypothesised that weak intermolecular interactions, H-bonding, and π electron delocalisation play a role in creating a polymer-protein composite. A restricted cell culture experiment set has demonstrated that nanoplastics may harm the immune network. Adverse impacts of nanoplastics on living organisms encompass the stimulated cytokine release linked to stomach disorders, interference with Fe conveyance, stimulation of programmed cell death, disruption of endoplasmic reticulum homeostasis, and oxidative damage. Nanoplastics have already been identified in various aquatic creatures, including prawns, fish, and shellfish. Furthermore, these minuscule plastic particles have been detected in diverse consumables like table salt, sweeteners, honey, etc. The latest infrared spectral analysis investigations have also demonstrated nanoplastics in domestic, bottled drinking water, and aquifer-sourced water. From 159 specimens of domestic drinking water obtained worldwide, 81% were discovered to harbour nanoplastics, predominantly particles less than 0.5 μm , with an average of 5.45 nanoparticles per litre. Of 259 mineral water bottles collected from 11 distinct labels and 27 diverse batches, 93% exhibited plastic pollution, with a mean of 10.4 fibres per litre. The migration or release of chemical supplements from the polymer substances could also impact individual well-being. In the plastic production method, substances like elastomers, colourants, or stabilising agents are introduced to impart the intended characteristics of the ultimate item, such as its elasticity, hue, and durability. Numerous chemical additives can seep into the surroundings throughout an item's existence, resulting in hormonal disturbance or severe toxic response upon interaction with humans. The identical factors are relevant for the structural units employed in producing the plastics initially (wherein trace levels might persist in the plastics) and the outcomes generated through the breakdown of plastics. Bisphenol A is the most notable instance of a seeping structural unit, which synthesises epoxide and polycarbonate. Research indicates that bisphenol A induces unfavourable impacts in organisms because of its hormone-mimicking, contributing to various metabolic disorders and affecting fertility and maturation processes. Specifically, plastic mineral water bottles utilised for infants exhibited substantial seepage of bisphenol A. Infants possess an elevated vulnerability compared to grown-ups, as an increased organismic load is anticipated, articulated as the amount in circulatory fluid, owing to heightened absorption or diminished removal in contrast to the organismic load of grown-ups.

Gastrointestinal noxiousness

After penetrating the gastrointestinal tract with food items, certain micro- and nano-plastics gather in the stomach and intestine, resulting in structural impairment. Plastic fragments measuring less than 150 micrometres were absorbed by lymphoid cells, triggering the reactive oxygen species generation and inflammatory response, weakening gut immunity, and damaging lipid catabolism and gut microbiota. For instance, cellular alterations in the gastrointestinal tract were observed in Purewater Benthic Clams contaminated with polystyrene (PS), evidenced by the disruption of the intestinal lining, an escalation in harmful microorganisms, and cell death. The research revealed nanoplastics in rodents' stomach, gut, and hepatic systems. Liang and co-authors investigated the impacts of 3 plastics of different sizes on the mucosal epithelium of rats (Liang et al., 2021). Following 1 day of contact, the body's plastic concentration elevated, and the barrier penetration enhanced, primarily due to reactive oxygen species-induced intestinal cell self-destruction. DeLoid and co-authors established an in vitro multicellular gut epithelial system, examining the absorption and harmfulness of PS plastic of various dimensions (DeLoid et al., 2021). They discovered that smaller particles were more readily penetrated cellular structure, leading to decreased cellular integrity and increased epithelial barrier penetrability. The gastrointestinal tract, the initial focal point of nanoplastics, has been examined in specific investigations to explore its detrimental impacts and modes of operation. The research predominantly focuses on marine species, but the toxicological data is absent. Furthermore, gastric fluid's impact on plastics' characteristics was not considered.

Toxic effects on lungs

Research has indicated that prolonged contact with plastics among individuals involved in polymer manufacturing not only increases the risk of various breathing disorders but is also associated with a heightened likelihood of developing pulmonary cancer. After introducing nanoplastics into the lower breathing passage of humans, they instigate the generation of reactive oxygen species (ROS), cytokine release, and programmed cell death, subsequently leading to detrimental effects on the pulmonary system. Additionally, it was determined that PS triggered the production of reactive oxygen species and respiratory epithelial cell inflammation. This led to the disruption of the lung epithelial barrier, adversely impacting the regular functioning of the respiratory system. In the study conducted by Lu and co-authors, it was observed that both healthy and asthma-prone rats, after contact with microplastics via the pulmonary canal, manifested clear signs of swelling and asthma attacks in their pulmonary regions, encompassing the immune cell invasion, macrophage accumulation, and inflammatory mediator release (Lu et al., 2021). The most recent investigation delved into the adverse impacts of PS particles on human pulmonary lining cells by employing two-dimensional and three-dimensional multicellular culture frameworks; the researchers scrutinised the disturbance of the respiratory mucosal barrier. Their hypothesis suggested that PS particles, inducing oxidative stress, were a fundamental factor in initiating cell swelling. Nonetheless, the precise mechanistic pathway underlying breathing disorders induced by plastic particles remains unexplored.

Neurological damage

Nanoplastics have been demonstrated to penetrate the neurological system through the brain endothelial barrier, bulbus olfactorius, and nervus olfactorius, to lead to detrimental effects. Studies suggest that diminutive plastic particles can infiltrate the nervous system of marine species, leading to oxidative damage and heightened susceptibility to brain disorders. Furthermore, nanoplastics hindered acetylcholine hydrolase function and interfered with neurochemical messenger concentrations. Researchers have substantiated that zebrafish exhibited altered neural patterns following ingestion of 70 nm PS particles. These alterations are primarily observed as notable modifications in locomotive activity, aggression levels, and anti-predator response. Moreover, laboratory condition studies demonstrated that exposure of astrocytoma cells to microplastics could prompt oxidative stress and swelling, resulting in considerable neurotoxic effects. Contact with microplastics solely or in conjunction with copper metal elevated the death ratio of zebrafish larvae, inducing neurological behaviour disorders and diminished swimming tendency. Kwon and co-authors suggested that PS particles smaller than 2 μm may infiltrate the rodent nervous system, accumulate in nervous tissue cells, and trigger microglial inflammation, leading to cytokine secretion and programmed cell death (Kwon et al., 2022).

Fertility impairment

Nanoplastics have been shown to breach the living partition and accumulate in genitalia, posing potential risks. After rodents were supplied microplastics by mouth for 28 days, tissue specimens showed that spermatocytes were shed, prokaryotic lymphoid invasion, reduced blood testosterone levels, increased testicular inflammatory cytokines, and deformed sperm cells. The same findings were observed where PS particles adversely affected the testicles of rodents, leading to deformed sperm cells, imbalanced hormonal concentrations and reduced fertility. Liu and co-authors investigated the detrimental effects of PS particles on the genital system of female rodents. They demonstrated that microplastics caused a decline in the follicular count and restrained ovum state and growth (Liu et al., 2022). Similarly, the findings of trials with mice also indicated a decrease in the follicular count and hormonal levels, affirming that PS triggered oxidative damage and ovarian scarring. After instilling PS particles in pregnant mice, the fetal uptake rate elevated, and the count and size of uterine blood vessels diminished. Simultaneously, there were notable alterations in the components of white blood cells in the fetal membrane, indicating that contact with microplastics triggered immunodeficiency, resulting in severe childbirth results. Fauna findings indicated that prolonged contact with plastic particles could pose harmful impacts on animal reproduction, and it could also be a potential threat to fertility issues in human beings.

Toxic effects of organic pollutant adsorbed nanoplastics

Confusion arises regarding the potential of nanoplastics to amplify the toxicity of organic pollutants. Numerous research studies have indicated that toxic effects may significantly increase owing to the substantial uptake power towards organic pollutants like Bisphenol A and chlorinated biphenyls (Okoye et al., 2022). Increased uptake could lead to increased aggregation. Indeed, other researchers have noted an opposite pattern, where increased uptake led to diminished toxigenicity. The amount of nanoplastics significantly influences

the adsorption. For example, at meagre amounts (0.4 mg/L), the pyrene attached to nanoplastics constituted below 1% of the overall pyrene aggregation in marine polychaete worms. Pyrene is predominantly easily obtainable in this scenario, so nanoplastics exerted minimal influence on its toxic behaviour (Sun et al., 2023). Additionally, the size of nanoplastics impacts the number of accessible adsorption centres, hence impacting the adsorption coefficient. (Table 2). For example, Velzeboer and co-authors discovered that nanoplastics increased the adsorption of chlorinated biphenyl in contrast to microplastics (Velzeboer et al., 2014). Differences in organic pollutants' water-resistant or polar nature yield distinct adsorption capabilities. The partition coefficient for water-resistant organic pollutants is greater than 1, indicating it can adhere to nanoplastics. Polarisation influences the sorption process, as polarised molecules adhere to nanoplastics via surface adhesion, while non-polarized molecules adsorb within the core structure of nanoplastics. This can result in differences in movement and bioaccessibility.

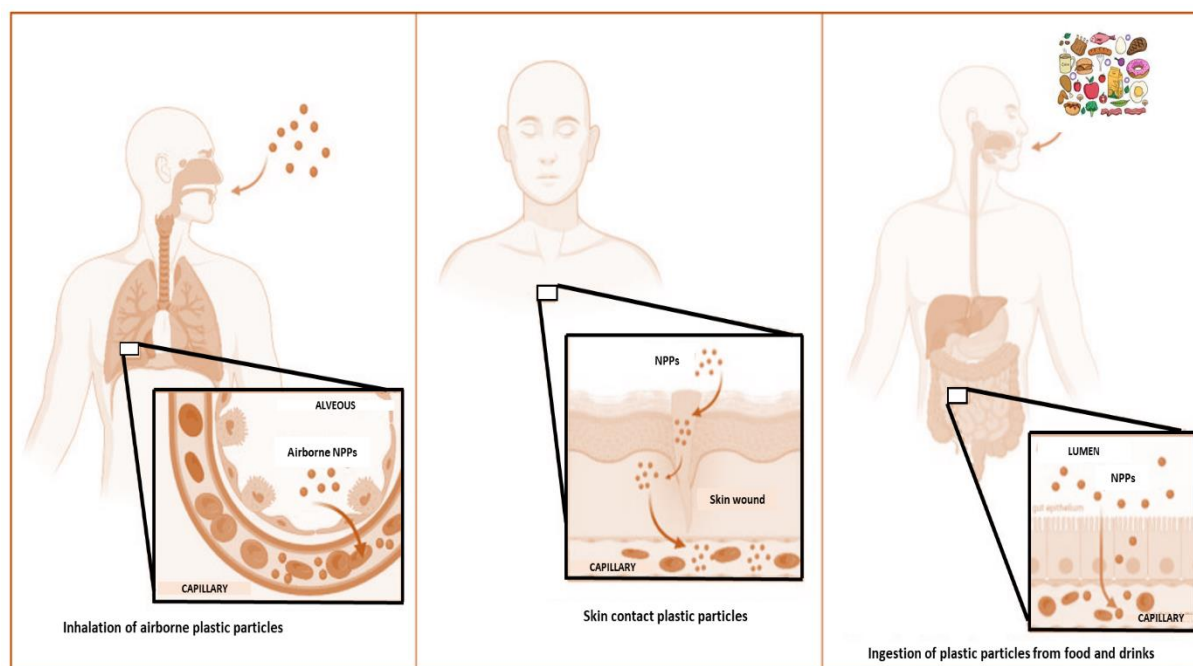


Fig. 4 The primary pathways for nano plastic particles to infiltrate the human biological system (Rashed et al., 2023)

Table 2 Relationship between nano plastic pollutants and ecological toxicants (Ali et al., 2021)

Plastic Type	Environmental Contaminant	Nanoplastic Pollutant Amount	Environmental Contaminant Dose	Adsorption capability
Unused polyethylene (PE)	Cr^{6+}	14 g/L 14g/L +2mM sodium dodecyl benzene sulfonate	100 mg/L	0.32 mg/g 1.39 mg/g
Unused polyethylene terephthalate (PET)	Cu^{2+} , Zn^{2+}	0.5 to 2.5 g	5 mg/L	Cu^{2+} : 40.3 to 55.1 $\mu\text{g/g}$; Zn^{2+} : 24.7 to 44.5 $\mu\text{g/g}$
Unused polyamide (PA), PE, polypropylene (PP), polyvinyl	Cd^{2+}	0.1 g	10 mg/L	PA (339.6 $\mu\text{g/g}$) > PE (234.5 $\mu\text{g/g}$) > PP

chloride (PVC), PS				(199.2 µg/g) > PVC (222.2 µg/g) > PS(69.9 µg/g)
Unused PS	Phenanthrene	50 mg	300 µg/L + 200 mg/L (NaN ₃)	170 µm (290 mg/kg), 102 µm (350 mg/kg), 50 µm (400 mg/kg), 30 µm (405 mg/kg), 0.8 µm (435 mg/kg)
Unused PS	Nitrobenzene	50 mg	30 mg/L + 200 mg/L (NaN ₃)	170 µm (105 mg/kg), 102 µm (2300 mg/kg), 50 µm (4800 mg/kg), 30 µm (5800 mg/kg), 0.8 µm (7000 mg/kg)
Unused PS, PP, PE	9-NAnt		500 ug/L	PE (734.35 µg/g) > PS (687.51 µg/g) ≈ PP (684.41 µg/g)
Unused PS	BPA	0.5 g	500 µg/L	6.9 µg/g
Unused low-density polyethylene (LDPE)	BPA	0.5 g	500 µg/L	1.2 µg/g
Unused PP, PVC, PE, PS	TYL	0.005–0.03 g	5 mg/L + 0.001 mol/L NaN ₃	PE (639.97 mg/kg) < PP (837.68 mg/kg) < PS (1346.85 mg/Kg) < PVC (1543.65 mg/kg)
Unused PS	HEX, MYC, TRI	100 mg (2 µm)	100 µg/L	HEX (42.72 µg/g) > MYC (19.49 µg/g) > TRI (11.27 µg/g)
Unused PE, PS	SMX, SMT, CEP-C	20 mg	2 mg/L	Freshwater: PS: SMX (90 mg/g) > SMT (60 mg/g) > CEP-C (55 mg/g) PE: SMT (55 mg/g) > CEP-C (43 mg/g) > SMX (0 mg/g)

High Molecular Weight Polyethylene (HMWPE), Ultra-High Molecular Weight Polyethylene (UHMWPE), PS, PP	IBU, DCF, NPX,	0.6 g	2.5 mg/ L	UHMWPE >HMWPE > PS > PP
Unused PE	CAR, DIP, DIC, DIF, MAL, DIFE	10 g/L	0.05–2.0 mg/L	DIF (645.461 µg/g) >DIFE(167.248 µg/g) > MAL (10.214 µg/g) > CAR (4.213 µg/g) > DIP (3.094 µg/g)
Unused PS	ATV, AML	5.0 g/L	10 mg/L	ATV (1.2 mg/g) > AML (0.28 mg/g)
Unused PP	TCS	20 mg	10 mg/L	25 mg/g

Early-detection methods

It typically requires researchers many years to formulate the notion of nanoplastics unavoidably, as there is sufficient proof suggesting that polymer materials decompose into nano-sized materials and persistently remain identifiable throughout the surroundings and unwillingly, as their broader dissemination and more challenging separation techniques in contrast to microplastics will result in more rigorous risks to organisms and the environment. To gain a deeper comprehension of the hazards linked with nanoplastics, a DPSIR (driving forces – pressures – states – impacts – responses) technique is utilised, as shown in Fig. 5. Nano-sized plastics in the surroundings might present hazards to land- and water-based living creatures. Nanoplastics could also jeopardise human well-being via the food web, breathing, and skin contact. Consequently, it is essential to explore hazard alleviation approaches in the mitigation of nanoplastics involving the formation of innovative remedial approaches, the formulation of guidelines, and the improvement of ecological knowledge. Because of the significant education deficit concerning nanoplastics (for example, their quantity in the surroundings, ecological patterns, and contact routes), difficulties persist in evaluating threats related to nanoplastics. To gain a deeper comprehension of the hazards linked with nanoplastics, considerable research initiatives are forthcoming. The initial stage involves obtaining sturdy information on contact in aquatic, pure water, and land-based environments. Presently, they are exceedingly restricted owing to the absence of accurate diagnostical methods; thus, the ecological amounts of nanoplastics are solely approximations.

Optical recognition/categorization

After extracting nano-sized plastic materials from the substance in which these nano-polymer particles are sampled, it is crucial to measure them precisely. It is widely acknowledged that, for micro-sized plastic particles, optical recognition/categorisation is a vital and mandatory step. This procedure can be carried out through unaided vision or a stereomicroscope, a practical approach extending to 500 µm. Nevertheless, numerous researchers have outlined instances where presumed nanoplastics were recognised as organically existing filaments and substances. This results in the proclamation that optical recognition results in less exaggerated plastic prevalence evaluations. So, despite numerous findings regarding the occurrence of nanoplastics depending on the amalgamation of optical recognition approaches and spectrometric techniques. Some rely exclusively on optical recognition techniques, which might not accurately depict the actual occurrence of these pollutants. Specific structured procedures have been established to minimise human

mistakes, encompassing examinations through light microscopy limited to only 1 mm and below particles. However, optical recognition is an inexpensive, uncomplicated, on-site, and comparatively speedy method.

Heat-induced decomposition – mass spectral analysis

Heat-induced degradation methods like thermal cracking, in combination with vapour phase chromatographic



Fig. 5 The DPSIR model for evaluating the risks associated with nanoplastics(L. Wang et al., 2021)

technique linked to mass spectral analysis, are invasive methods permitting the recognition of the plastic composition of micro-sized plastics is done by examining their heat decomposition substances. Both Pyrolysis GC /MS and Thermal Evolved GC/MS offer the benefit of removing preliminary stages and enabling the simultaneous recognition of numerous particles without the necessity for separate categorisation while requiring a small number of specimens(Pico & Barcelo, 2020). It also facilitates the concurrent recognition of organic materials bonded with plastics. Still, these heat-based decomposition methods do not enable the structural analysis of the examined specimens, encompassing quantity, dimensions, and colour, but instead, the weight of these specimens. Furthermore, despite requiring only small specimen quantities, in the case of Pyrolysis GC/MS, particles must be inserted into the pyrolytic reactor by hand. Since specimens can only be adjusted up to a specific size threshold, this limits the examination of nano-sized particles and could jeopardise the inclusiveness of the specimen, particularly in intricate substances, as homogeneity may not be assured at a nanoscopic level. Due to the constraints of Pyrolysis Gas Chromatography/Mass Spectrometry on small amounts, it obstructs its utilisation in scrutinising substantial volumes of specimens, making it unsuitable for efficient processing analysis. These constraints can be overcome by turning to Thermal Evolved GC/MS(Dehaut et al., 2020). This enables the application of significantly increased specimen weights (up to 200-fold more significant than in Pyrolysis GC/MS) and relatively rapid examination and mass assessment durations, especially for prevalent plastic varieties such as PE, PET, PS, and PA. Nevertheless, the analysis of particles and the structural examination of separated substances continue to pose a significant constraint in this approach(Enyoh et al., 2021). It has been confirmed exclusively for the previously mentioned prevalent plastic varieties and has not undergone scientific verification for alternative plastics like polycarbonate and PVC(Seeley & Lynch, 2023).

Raman analysis

This non-intrusive spectrometric method facilitates the examination of low-energy vibrations within a system, encompassing vibrational and rotational coupling(Lv et al., 2020). It is a simple method that offers a molecular

imprint and has been effectively used to identify nanoplastics in various ecological settings. As plastic materials showcase distinctive Raman patterns, this method allows for the recognition of presumed particles in a small amount of time. Optically arranged particles can be easily examined, and when combined with Raman imaging, particles with dimensions of less than 1 μm can also be effectively recognised (Mogha & Shin, 2023). By integrating Raman imaging with methods like Raman spectroscopic imaging, it is feasible to capture photographs reflecting chemical mapping, and theoretically, spectroscopic examination of entire microporous filters with elevated image sharpness (less than 1 μm) is attainable. This has the potential to streamline the recognition/categorisation of diminutive particles, although, at present, its suitability in the investigation of nano-sized plastic materials remains unverified. Another plausible integration involves Raman scattering with confocal imaging, potentially enabling the recognition of plastics within cellular elements with intracellular accuracy. Paired with scanning probe microscopy, Raman spectroscopy has the potential to facilitate the recognition of plastic particles, employing scanning probe microscopy in both tactile and non-tactile modes. Nevertheless, it would be challenging and lengthy to locate and centre the Scanning Probe Microscopy-Raman laser on an individual small particle and, therefore, even if convincingly proven as a practical substitute for recognising plastics in ecological specimens, it would not be practical in examining numerous specimens (Vélez-Escamilla & Contreras-Torres, 2022). However, there are still some limitations in using Raman spectrometry to examine plastic particles. For instance, samples that exhibit fluorescence when stimulated by the laser produce Raman spectroscopic profiles that cannot be effectively comprehended due to the inconsistent baseline resulting from the laser-excited fluorescence perturbation. Hence, it is advisable for specimens intended for Raman analysis to undergo preliminary filtration stages to minimise fluorescence. Moreover, the system variables for Raman have not been universally uniform, and numerous scientists tend to employ their individual choices, encompassing frequently utilised laser frequencies such as 532 nm and 785 nm. Increased frequencies might lead to diminished fluorescence disturbances, yet the reduced energy of the laser will yield diminished spectral patterns from the polymer specimens (Adhikari et al., 2022).

Fourier-transform infrared analysis (FTIR)

This technique resembles Raman scattering, which precisely recognises plastics relying on their infrared absorption patterns. Indeed, Infrared and Raman techniques can be seen as mutually supportive analyses, given that vibrational modes inactive in the infrared spectrum are active in Raman, and conversely (Delgado-Gallardo et al., 2021). To put it briefly, Raman analysis depends on photonic dispersion, while infrared relies on absorption. Similarly to Raman analysis, the infrared spectral patterns produced for plastics are exceedingly precise and showcase unique signals. IR can, furthermore, furnish additional insights into the ageing of polymer specimens, efficiently enabling an assessment of the extent of deterioration or even decomposition, depending on the magnitude of the oxidative process (Enyoh et al., 2021). This might be accomplished, for instance, by gauging the carbonyl content, as the generation of carbonyl moieties has been linked to the oxidation of materials. Bigger particles can be readily examined using a surface modification of IR, referred to as total internal reflection absorption (Chen et al., 2020). Based on the specific empirical parameters, each specimen can be unmistakably recognised in under 1 minute. However, it is necessary for the specimen to be separated and, preferably, totally devoid of moisture to prevent infrared spectral patterns originating from the liquid. Regarding utility, when dealing with a relatively small sample size, such as 100, it has been proposed that recognising more than 50% as a typical subset is advisable. By integrating microscopy with IR, gathering infrared spectral patterns at elevated image sharpness becomes feasible, given that the beam dimensions can be as diminutive as 5 μm . This offers significant potential for the comprehensive analysis of specimens with intricate compositions. Indeed, past studies indicate that micro-IR-based recognition of plastic particles has emerged as the predominant empirical method. However, these technologies must contend with a rising quantity of specimens, each having expanding amounts of plastics. Moreover, producing, studying, and saving the spectral patterns is necessary for every one of these. Consequently, a promising expansion of IR is the implementation of sensor grid-based micro-IR, facilitating the investigation of the complete set of particles on a filtration medium with elevated efficiency, devoid of any mistakes, substantially reducing time requirements essential for deciphering intricate visual data while concurrently enhancing data excellence. Nevertheless, the number of spectral patterns and the requisite memory space might necessitate robust and costly hardware, and up to 1.8 million patterns could be produced from only a handful of information. A more straightforward option could involve fluorescent labelling followed by micro IR analysis, a method proven to lead to reduced measurement exertion. Due to the solvent-sensitive properties of Nile Red—it's capacity to alter colour in response to shifts in solution medium property—there is potential for a comprehensive classification of plastics based on the surface reactivity attributes of the recognised particles. This approach might be semi-autonomous

if it is integrated with static image examination, leading to a simultaneous reduction in mistakes and prejudices, while this remains unconfirmed.

Matrix-enhanced laser ionisation time of flight mass spectrometry

Matrix-assisted laser desorption/ionisation time-of-flight mass spectrometry is a resilient method for examining plastics, which can also be employed to differentiate polymers. Samples are gently ionised following laser ionisation, enabling the detection of ionised signals in both high-molecular-weight and low-molecular-weight zones (Lin et al., 2020). This is conducive to detecting various polymers based on their ion formation tendencies. For instance, characteristic signals at mass-to-charge ratios of 104, 90, 130, 128, 312–318, and recurring signals at a mass-to-charge ratio of 104 within the mass-to-charge ratio range of 350–

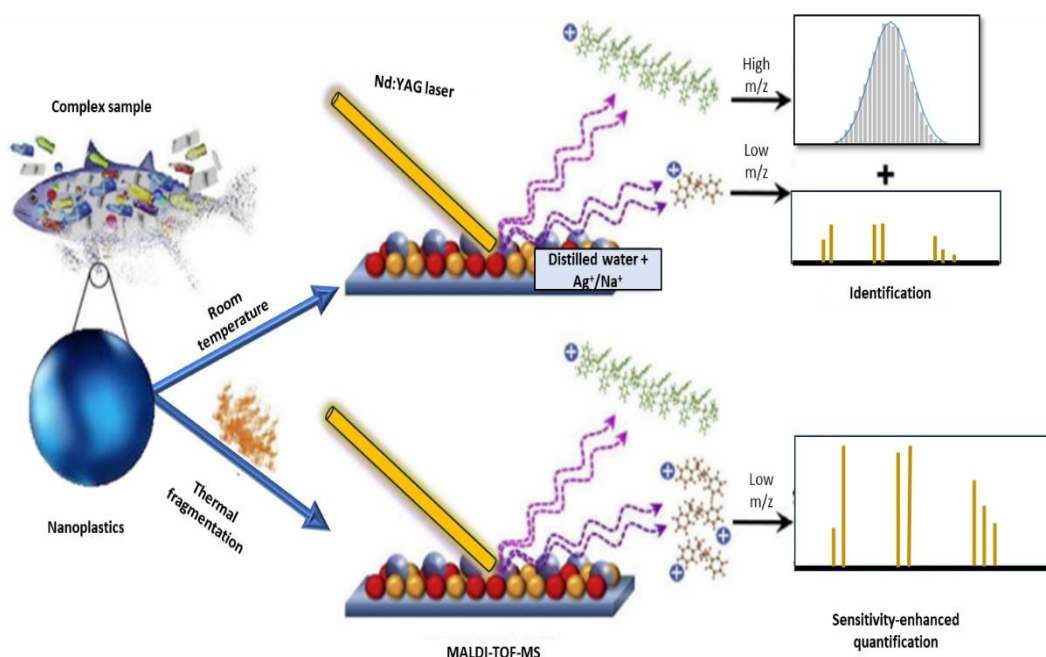


Fig. 6 The process for heat-assisted detection and measurement of polystyrene nanoplastics using matrix-enhanced laser (P. Li et al., 2020)

Five thousand can be utilised to differentiate PS. Subjecting polystyrene to pyrolysis at 380 °C for 10 minutes expedited the breakdown of polymer chains, leading to a notable enhancement in the signal strength within the lower mass-to-charge ratio ranges. This facilitated the measurement of nanoplastics, as depicted in Fig. 6. The assessment of PS in intricate specimens like seafood and stream water was also achievable.

Water pollutant sources and their transport routes

Potable water can be obtained from two fundamental origins: fresh aboveground water (lakes, rivers, estuaries, etc.) and aquifers. The aquatic environment harbours unintentional and human-made pollutants, as shown in Fig. 7 (Gong et al., 2023). In this context, aquifers are more secure than reservoirs as they are less susceptible to contamination. Naturally occurring impurities infiltrate water from the geologic layers via which the water travels. Human-made pollutants contaminate the aquatic environment from various origins, including factory effluents, agrochemicals runoff, and wastewater treatment facilities (Vaseashta & Maftai, 2021). It is approximated that around 1407 types of disease-causing microbes have the potential to contaminate the human body via potable water intake (Kordbacheh & Heidari, 2023). These pathogenic microorganisms comprise viruses, bacteria, parasites, fungi, and worms (Tang et al., 2019). Cholera bacterium, Shigella, Salmonella, E. coli, Campylobacter, and Yersinia are well-known pathogenic bacteria in the water. At the same time, the Hepatitis E virus, Hepatitis A virus, Human caliciviruses, Rotaviruses, and Enteric adenoviruses are several examples of viruses. Cryptosporidium, Giardia, Microsporidia, Cyclospora, and Entamoeba histolytica are notable examples of parasitic protozoa. Animal and human excreta constitute the primary origins of microorganisms and virus-induced pollution in drinking water. Numerous chemical contaminants in potable water are subject to regulation by the World Health Organisation and the United States Environmental Protection Agency. Chemicals like nitrite, nitrate, fluoride, pesticides, heavy metals, and polycyclic aromatic hydrocarbons in water cause attention; out of all substances, nitrate is one of the most frequently found

pollutants worldwide. The origins of fluoride include minerals such as gemstone, fluorapatite, fluorapatite, phosphorite, and cryolite. Agrochemicals and their breakdown by-products infiltrate aquatic environments through agricultural activities. Water reservoirs may experience polycyclic aromatic hydrocarbon contamination via human-made and various natural activities or the bio-transformation of hydrocarbons (Sall et al., 2020). Wastewater purification using chlorine is the primary cause of trihalomethane generation, resulting from the interaction of free chlorine with inorganic chemicals and organic matter in water. Aquifers and fresh aboveground water are contaminated with trace elements from natural and human-made sources (such as manufacturing, farming, and extraction). Potable water includes natural radioisotopes (such as uranium, radium, etc.) resulting from minerals like uraninite and monazite sand, along with artificial radioisotopes (such as caesium, strontium, etc.) originating from radioactive fallout and incidents at nuclear power plants (Sankhla et al., 2016). Trace metal contamination of above-ground and subsurface water origins leads to significant land contamination (Wasi et al., 2013). The extent of contamination escalates when mineral deposits are discarded on the surface level for hand processing. Landfilling subjects the metal ions to the atmosphere and waterways, causing metal leaching. When agro lands are contaminated, the heavy metals are absorbed by green plants and subsequently aggregate in their cellular structures. Organisms that forage on such polluted vegetation and consume water from polluted sources, along with aquatic species that reproduce in contaminated waters, also amass these heavy metals in their cellular structures. Human beings encounter such metals through the intake of polluted fauna and plants, and it causes several metabolic imbalances.

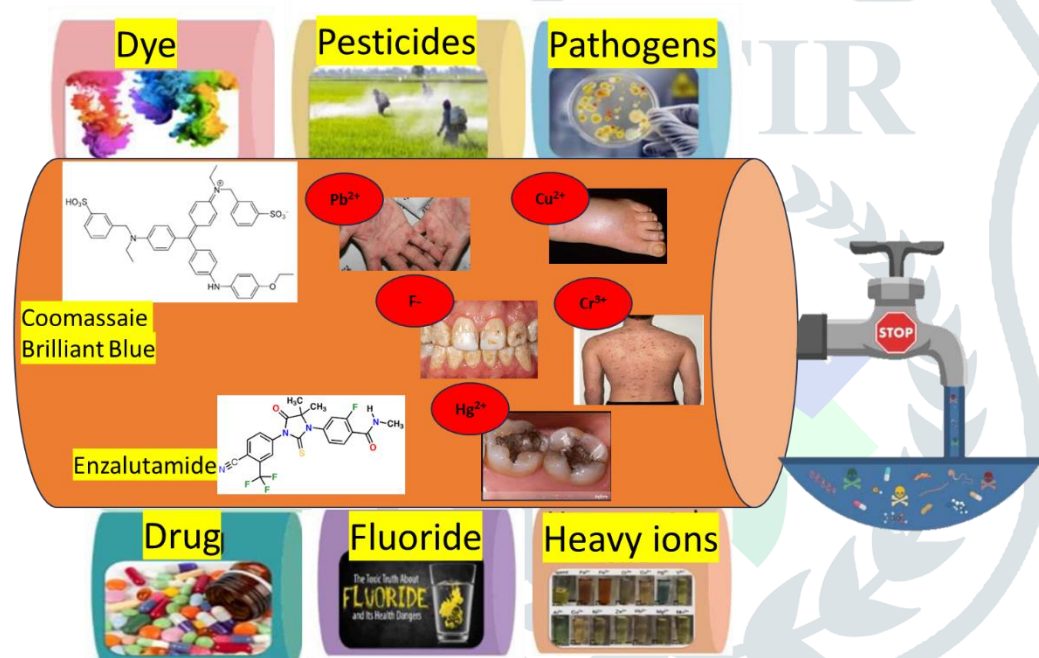


Fig. 7 Various Origins of Water Contaminants (Kordbacheh & Heidari, 2023)

Toxic effects

Trace metallic ions can induce severe health issues in the human body, impacting renal, hepatic, and pulmonary functions. Most of the heavy metals are cancer-causing. They can lead to impediments in the maturation of the human body and disturbance of biological control mechanisms accountable for operational or psychophysiological syndromes, such as myalgic encephalomyelitis and degenerative brain diseases, such as Alzheimer's and Parkinson's (Lin et al., 2022). Exposure to trace metals like Pb^{2+} and Hg^{2+} can also result in immune-mediated diseases, wherein the individual's brain targets their cells. This may result in disorders like cardiovascular, rheumatoid arthritis, renal, and neural issues (Haseena et al., 2017). Heavy metals can exert considerable toxicity on microbes, thereby influencing their development, structure, and physiological functions due to tissue bonding. Exposure to certain trace metals can result in structural changes and genetic mutations witnessed in green plants. These comprise root reduction, leaf desiccation, yellowing, shortage of nutrients, and heightened susceptibility to insect infestation. Similarly, the proliferation of microorganisms is impeded or entirely suppressed at elevated trace metal concentrations. Heavy metals show their toxic effects through various mechanisms, such as displacing vital metallic ions from their active regions on organic substances, hindering catalytic activity, and disrupting nucleic acid structure (Verma & Ratan, 2020). There are many studies published on the toxicology of heavy metals, pesticides, etc., present in water on the human body (Bansal, 2020; Seth, 2014; Wimalawansa, 2016; Zuo et al., 2018).

Methods for detection

Microbial fuel cell (MFC) detectors

These detectors are utilised to detect water quality issues early. They can be employed to oversee various water environments, including but not limited to lakes, wetlands, and water purification facilities (Zhou et al., 2017; Sonawane et al., 2020). The design and functionality of sensors may need to be adapted based on the specific characteristics and surveillance necessities of the particular aquatic environment (Cui et al., 2019). Organic aquatic environments generally experience infrequent water condition disruptions. Owing to the rarity of these disturbances, most microbial cell biochemical oxygen demand detectors designed for organic aquatic environments underwent analysis within controlled lab settings, utilising aquatic specimens obtained from proximate areas. In various laboratory and field scenarios, it is imperative to routinely assess the detector's functionality, which can be accomplished by subjecting it to a quality assurance benchmark. The implementation of quality control is essential for rectifying any deviations in detector data as anodic microbial films, flow patterns, and various elements influencing power production can undergo alterations gradually. An autonomously powered distant system is typically necessary for overseeing organic aquatic environments. Apart from detectors for observing water purity, the setup should incorporate a renewable energy origin (to energise the entire system) and a radio frequency data sender (Do et al., 2020). A significant benefit of a microbial cell detector is that it can act

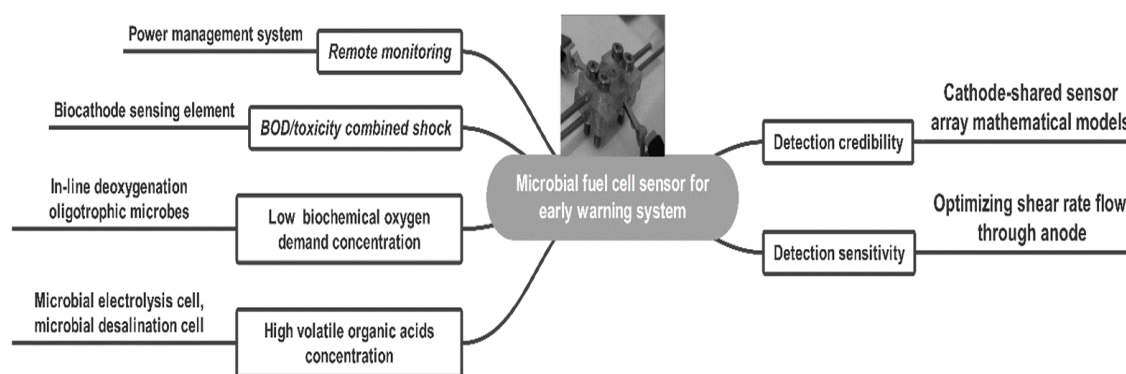


Fig. 8 Microbial

fuel sensor for detection of water quality (Jiang et al., 2018)

as an energy provider. A self-sufficient, budget-friendly microbial cell detector was built by merging four parallel linked microbial cells with an energy control system (El Mekawy et al., 2018). Nevertheless, the activation duration of the microbial detectors was notably extended compared to the microbial cell potential fluctuation. This is because the microbial detector's energy produced served as the electric circuit's exclusive energy supply. As a quickly advancing technology for assessing water purity, MFC detectors have undergone extensive research in the last ten years, particularly in biochemical oxygen demand and hazard assessment (Kumar et al., 2022; Sun et al., 2015). The advancements in MFC detector technology for early warning systems are shown in Fig. 8.

Electroanalytical method

Typical methods, such as chromatography, necessitate specific pre-processing steps, potentially leading to time-consuming processes. In this context, electroanalytical detectors and specific lesser diagnostic devices have proven invaluable tools for detecting minute specimen amounts (Díaz-González et al., 2016). Ongoing advancements have been achieved in producing and applying electroanalytical detectors for crops, pharmacy, and environmental assessments (Sivaranjane et al., 2022). Electroanalytical methods for identifying toxins can be categorised as electrical conductivity, cyclic voltammetric, and potential-based (Patel et al., 2020). The ability to design particular recognition renders detectors a viable alternative to traditional separation methods (Karthik et al., 2022). Electroanalytical detectors offer numerous benefits compared to already present detectors, including continuous surveillance, downsizing and enhancement in responsiveness and specificity (Hernandez-Vargas et al., 2018). Additionally, electroanalytical reactions transmit electromagnetic impulses, eliminating the necessity for intricate electric pulse elements. This promotes the enhancement of precise healthcare analysis systems and the surveillance of nearby surroundings. Bio-detectors employing probes enable the conversion of physiological indicators into an interpretable output signal. The sensitivity and specificity of these indicators can be attained through calibration with particular biological systems, such

as genetic material, cellular structures, or protein catalysts. Due to the nature of biological transformation, electroanalytical detectors can be termed either enzymatic sensors. With biological elements capable of recognising a target and initiating an electrochemical process, enzymatic detectors undergo alterations. Later, electroanalytic affinity biosensors have a binding recognition element that emits a signal upon bonding with the target (immune proteins)(Zahran et al., 2021). The application of detectors for identifying detrimental pollutants in the surroundings, including lead, cadmium, mercury, and copper, is broadly prevalent(Tajik et al., 2021). Electrochemical science is a branch of Chemistry focused on the correlation of electronic and chemical phenomena, encompassing the assessment of parameters, like voltage and current, and their interplay with chemical factors. A substantial focus lies in exploring the chemical transformations induced by the passage of current and the conversion of such processes into electrical energy. A broad range of applications for empirical objectives has been identified using these measurements. In contrast to various chemical measurements that entail uniform solutions, electrode processes occur at the interface of the cathode solution. These processes are monitored using various electrochemical techniques(Martínez-Huitle et al., 2015). The variations among various electroanalytical techniques are rooted in the analytical signal employed. The two primary categories of electroanalytical detectors are Voltage-based and Amperometric. Voltage-based approaches entail measuring the cell voltage at no electrochemical current. The voltage is proportional to the log function of the amount of the analyte being analysed. Amperometric methods encompass a range of methods involving the application of a dynamically changing voltage between a working electrode and a standard electrode in a galvanic cell with a large amount of an inert electrolyte to form the current-carrying solution. The electric flow is consistently monitored across the cell. Amperometric biosensors consequently involve examining charge transfer at an anodic configuration interface. This process can be perceived as interlinked electron mass, compelling the substances to either gain or lose an electron, resulting in reduction or oxidation. The electric flow reflects the speed at which charge carriers traverse the electron-solution interface. Hence, these methods can be applied to analytes capable of undergoing reduction or oxidation. The electric voltage at the cathodic terminal remains elusive. Consequently, the voltage gradient between two electrodes is approximated. The terminal with a constant voltage is termed the standard electrode; the other is the indicator electrode.

Separation technique

The separation technique is used to segregate the amalgamation and gather both descriptive and numerical information(García-Córcoles et al., 2019).The process allocates portions between fixed and moving phases while the specimen crosses the moving phase. The portion whose partition coefficient favours the fixed phase will require more time to conclude the system, whereas those favouring the moving phase will necessitate a lesser duration for completion(Shafique et al., 2017).Separating soluble materials with comparable partition coefficients is feasible Given sufficient duration and both fixed and mobile phases. Separation technique is of different types, i.e., Vapour Phase Chromatography and Advanced Liquid chromatography(Carmona & Picó, 2018).

Vapour phase chromatography

In the Vapour Phase Chromatography, a vapour or liquid sample form is introduced into a stream of a mobile inert gaseous medium (commonly referred to as transport gas, such as He, Ar, or N)(Shafique et al., 2017). The specimen is conveyed through a compressed or thin-tube column, where the specimen constituent is isolated based on its capacity to scatter among the immobile and moving phases. Column heating regulation is crucial to achieve a satisfactory separation. The column is placed in a temperature-controlled oven. Sensors like Thermal detectors, Flame-ionizing sensors, Mass spectrometric analyzers, and an Electron capture sensor typically amalgamate the gas chromatograph. It is extensively applied in medical, ecological, medicinal, investigative, molecular biology, food chemistry, and petrochemistry labs to examine a broad spectrum of specimens. Vapour Phase Chromatography assesses different organic pollutants in the atmosphere and aqueous systems(Zulkifli et al., 2018). Preliminary steps and well-trained personnel are essential for these methodologies.

Advanced liquid chromatography

A specimen (fluid or dense substance soluble in an appropriate solution medium) is propelled in advanced liquid chromatography via a moving liquid phase across a separation column.Engagements between the solvating medium and the fixed phase govern 102 Distinction. The separation employs a solitary moving phase of consistent components in non-gradient elution. Generally, finding a singular moving phase component

applicable to all analytes is often challenging. The moving phase's components are intermediately hydrophilic to facilitate hydrophobic phase separation (Komorowicz & Barańkiewicz, 2011). The moving phase's components become progressively less hydrophilic as the partition progresses. Advanced Liquid Chromatography is employed for experimental and statistical medicinal, ecological, judicial, healthcare, and manufacturing analyses (Kanu, 2021; Hernandez et al., 2014). Typically, these separation methods are employed for the examination of hydrocarbons. Separation methods are highly effective and provide excellent responsiveness, particularly when coupled with mass spectrometry, but they necessitate costly and intricate tools that require skilled handlers (Gosetti et al., 2016).

Absorption analysis

Absorption analysis encompasses all diagnostic methods that employ the release and uptake of radiant energy by atomic elements (Aquisman et al., 2019). It is an excellent method for analysing small amounts of various components. The specific frequency of the irradiation identifies the components. The strength of irradiation correlates with the quantity of the components. There are two kinds of absorption analysis: Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma-AAS measures the photon absorption through the transition of atomic elements from the lower level to the excited states. The radiation intensity is determined utilising the Beer-Lambert Law, incorporating the extinction coefficient of the non-excited atoms. Heavy elements are extensively investigated through AAS by either Flame Emission Spectroscopy or Thermal Ionization (Sharma & Tyagi, 2013). The selection of the ionisation method is predominantly dictated by the amount of the elements in the samples being examined (Khaniki et al., 2017). Due to the heightened responsiveness of thermal ionisation, the detection threshold for most samples is significantly less than when employing flame emission spectroscopy. The higher precision in flame emission spectroscopy makes it the preferred method when the substance amount exceeds the flame ionisation identification threshold. However, flame ionisation is less prone to interference, considers a greater specimen processing rate, and demands limited handling expertise (Tsade, 2016). Inductively Coupled Plasma represents an atomic spectrometric method that employs ionised gas for the ionisation procedure. The ionised gas comprises many charge carriers, effectively nullifying and neutralising substances. Ionised gases play a crucial role in disassembling atoms and facilitating the atomisation and excitation, resulting in ion radiations. This technique offers smaller identification thresholds but requires handling expertise compared to the AAS method. The primary limitation of all atomic spectrometry techniques is their inability to provide information on the compound's oxidation state.

Fluorimetric analysis

This approach is valuable for identifying diverse contaminants such as organic pollutants, residual organic matter, and other contaminants in the sea, subsurface, and aboveground water (Khan et al., 2021). Presently, a range of techniques is employed for identifying water contaminants based on conventional approaches such as Machine learning networks and Vector Machines. Nevertheless, this method of water purification has numerous disadvantages. It is time-consuming, demands multiple chemicals for examination, exhibits reduced sensitivity, and produces waste products. Contrasted with the conventional approach to water purity identification, spectral analysis identifies contaminants without segregation or removal. This method is straightforward and swift, eliminating the need for chemicals to identify pollutants (Carstea et al., 2016). Numerous scientists employ Ultraviolet-Visible Spectroscopy to analyse water contaminants or assess water quality, making it a convenient and efficient approach. The identification threshold for specific organic compounds falls short of meeting the reference. Over the decades, fluorimetric analysis has been employed extensively in water purity assessment (Zacharioudaki et al., 2022). Moreover, it is the primary method for continuously detecting soluble organic compounds in fluid (L. Li et al., 2020). It identifies organic compounds at a smaller threshold than the ultraviolet-visible range. This approach necessitates a smaller specimen size and enables specimen detection without pre-processing steps (H. V.-M. Nguyen et al., 2023). Therefore, it is non-destructive. It exhibits high specificity and excellent reliability. The approach for detecting water contaminants relies on the absorbance of pollutants under ultra-violet illumination. This technique identifies water contaminants by capturing the radiation released by the pollutants following absorption at a distinct frequency (Okache et al., 2015). The mechanism of fluorescence-dependent identification of water pollutants is shown in Fig.9.

Colorimetry

Colorimetry offers precise outcomes regarding metallic elements or other pollutants in aquatic samples (Priyadarshini & Pradhan, 2017). However, this method is expensive and is exclusively accessible in advanced laboratories, making it difficult to use for on-site water pollution testing (Bendicho et al., 2021). Additionally, This method requires more time and skilful operators. Many water pollutants lack colour, rendering them undetectable to the naked eye. Multiple methodologies are employed to identify these, one such approach being Colorimetry (Rasheed et al., 2018). This method gauges the pollutant's reaction with a substance that produces a distinct colour. The chromatic strength correlates with the amount of the water pollutant; a higher colour strength suggests a greater concentration of the pollutant, indicating a direct relationship between colour strength and pollutant level (Prosposito et al., 2020). Using this method, the levels of different chemicals can be detected like ammonia, fluorine, phosphorus, zinc, trace metals, magnesium, etc. (Liu et al., 2020; Balusamy et al., 2020).

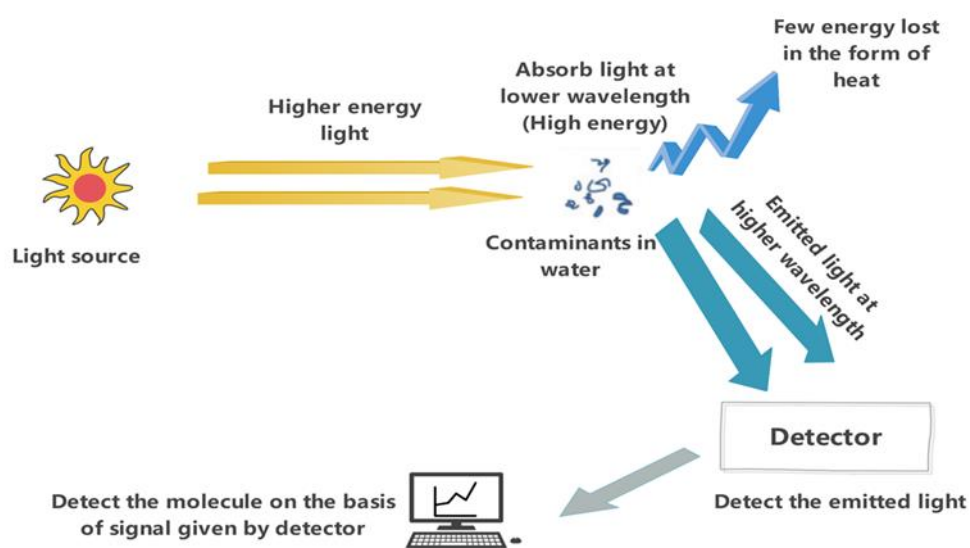
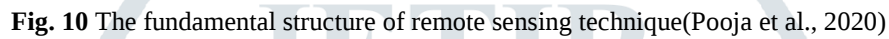


Fig. 9 The process of fluorescence-dependent identification of water pollutants (Pooja et al., 2020)

Remote sensors

The progression of water purity tracking models has evolved from practical laboratory techniques to on-site tracking and, more recently, to remote sensing techniques (Ramadas & Samantaray, 2018). In the conventional method, specimens were gathered manually and then supplied to labs for pollutant detection. However, this method necessitated skilled operators, specialised tools, and devices, was time-intensive and expensive, and lacked the capability for live tracking to assess alterations in water purity (Walczykowski et al., 2013). To address the challenges above, on-site detectors were devised for live detecting of water purity (Adu-Manu et al., 2017). This method led to the creation of handy tools capable of tracking water purity and preserving the information. Still, this method faced challenges in autonomously transmitting information to consumers for subsequent refinement. Wireless sensor networks are increasingly capturing the interest of scientists and final customers in tracking water purity (Andres et al., 2018). This surge in popularity can be attributed to the following reasons: in-situ installation of detectors for information gathering, the flexibility to adjust sample wavelength according to consumer's preferences without additional expenses or time, on-demand data interpretation by customers, and regulation of sensing devices remotely (Adjovu et al., 2023). A fundamental architecture of Wireless Sensor Networks comprises individual sensing points responsible for detection, data modulating, integrated system design, and linkage, as shown in Fig. 10. This configuration facilitates wireless interaction between individuals or computing systems and the surroundings through a cordless connection. The mechanism of remote sensors encompasses data collection, transfer, retention, and sharing. The transfer of information using the water purity detection technique relies on mobile networks or space-based data connections. Information can be preserved in



Wastewater-based epidemiology

Wastewater-based epidemiology is a detection method that involves analysing polluted water for the presence of diagnostic indicators that provide data about the health status of a community. This information gives a broader understanding of public health trends and can be helpful for timely responses to potential health risks in a community (Vitale et al., 2021). Real-time monitoring allows for the early detection of changes from the typical pattern, potentially enabling prompt responses to emerging health concerns (Choi et al., 2018; Mao et al., 2021). Due to price and supply chain hurdles, wastewater-based epidemiology offers benefits in contrast to biological tracking techniques that concentrate on a limited audience, but wastewater-based epidemiology covers a large population. Compared to conventional monitoring systems, this technique can offer prompt assessment, enabling swift governmental action and implementing potential medical actions before the contagion spreads (Jiménez-Rodríguez et al., 2022). Typically, for infectious illnesses, it is crucial to acquire two sets of data, specifically, disease-causing microorganism details and host-parasite

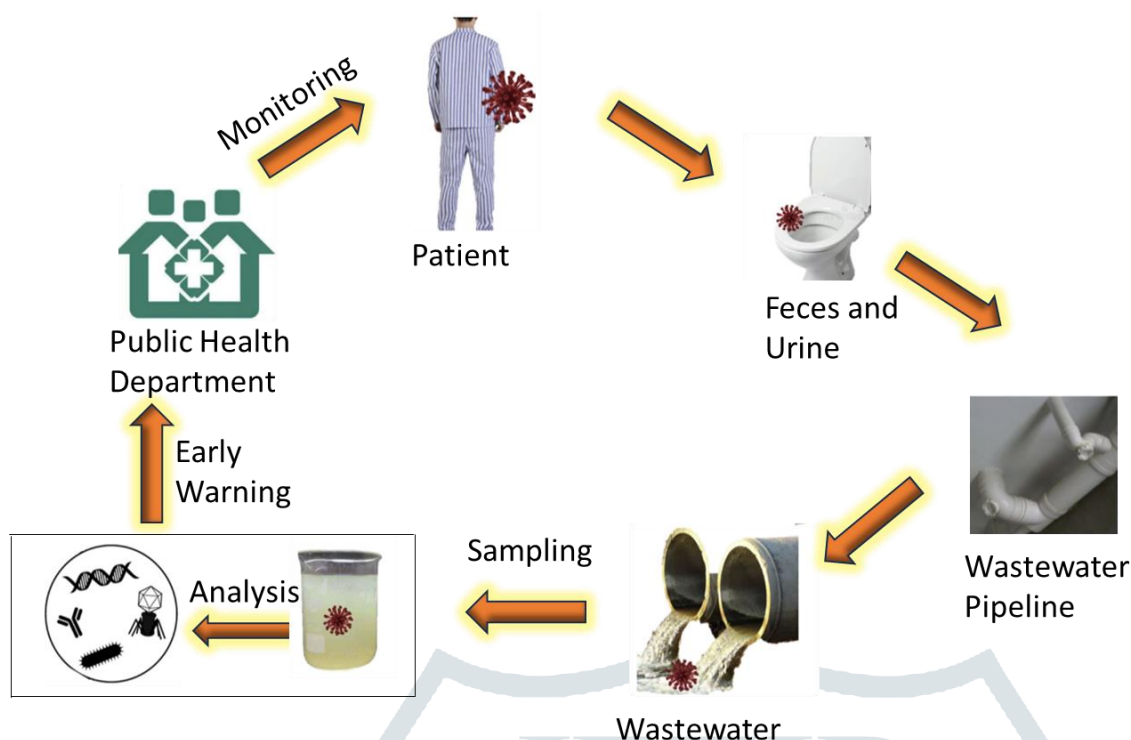


Fig. 11 Wastewater-Based Epidemiology as a monitoring system for detection of transmissible illnesses induced by pathogens(Mao et al., 2020)

data, which are biomarkers of disease(Mahmoudi et al., 2022). Recognizing disease-causing microbes, bacteria, etc., in sewage discharge can track the origin of microbe vectors via reverse tracing, thus pinpointing the region of illness dissemination in the community. In the context of the coronavirus pandemic, numerous scientists have employed this technology to identify the COVID-19 virus in polluted waterways, monitor possible disease carriers, and offer an early alert for health risks in the community. The host-pathogen data include symptoms like coughing and biological changes like immune system responses. In this technology, protein-based and nucleic acids are the most used bioindicators for tracking wastewater pollutants. This technique encompasses the retrieval, examination, data handling, and analysis of substances (commonly referred to as biological indicators) secreted from urine or stool in polluted water that gives extensive public health insights, as shown in Fig. 11. The polluted water is collected from specific locations, named as wastewater collection units. These collection points are situated in well-defined geographical areas known as polluted watersheds. It is crucial that the community collectively participates in gathering polluted water from a particular site, which serves as a comprehensive representation of the community's waste. The biological indicators originate from public secretions (like biological compounds arising from contact with illness) and affiliated microbes or bacteria, which can mirror the public's health state and lifestyle practices as they encompass abundant biochemical data.

Conclusion

The presence of emerging substances such as pharmaceuticals, nanoplastics, organic pollutants, pesticides, and personal care products in the environment continues to substantially threaten human well-being and marine ecosystems. These pollutants enter the environment via human activities and natural factors and have been detected in surface water, aquifers, soil, sediments, and drinking water. Cutting-edge analytical techniques have been developed to identify contaminants in the environment and the human body. In light of the prevailing circumstances, it is imperative to consider various elements when evaluating the impact of contaminant exposure on human health. These include the amount of pollutants, their characteristics, and the extent and magnitude of contaminants. Novel technologies must exhibit efficacy and environmental friendliness in detecting a broad range of emerging contaminants while maintaining sustainable energy use and minimal capital expenses.

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Abbreviations**NPPs** Nanoplastic particles**SPME** Solid Phase Microextraction**GC** Gas Chromatography**MS** Mass Spectrometry**PS** Polystyrene**ROS** Reactive oxygen species**PE** Polyethylene**PET** Polyethylene terephthalate**PA** Polyamide**PVC** Polyvinyl chloride**LDPE** Low-density polyethylene**HMWPE** High molecular weight polyethylene**UHMWPE** Ultra-high molecular weight polyethylene**PP** Polypropylene**TCS** Triclosan**9-NAnt** 9-Nitroanthrene**BP** Bisphenol A**TYL** Tylosin**HEX** Hexaconazole**MYCN** Myclobutanil**TRI** Ntriadimenol**SMX** Sulfamethoxazole**SMT** Sulfamethazine**CEP-CE** Cephalosporin C**IBU** Ibuprofen**NPX** Naproxen**DCF** Diclofenac sodium salt**CAR** Carbendazim**DIP** Dipterex**DIC** Dichlorovo**DIF** Diflubenzuron**MAL** Malathion**DIFE** Difenconazole**ATV** Atorvastatin**AML** Amlodipine

MFC Microbial fuel cell

AAS Atomic absorption spectroscopy

FTIR Fourier-transform infrared analysis

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